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Permalink

<https://escholarship.org/uc/item/2hs1d691>

Journal

Environmental health perspectives, 121(11-12)

ISSN

0091-6765

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Publication Date

2013-11-01

DOI

10.1289/ehp.1306967

Peer reviewed

Research on the Premotor Symptoms of Parkinson's Disease: Clinical and Etiological Implications

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BACKGROUND: The etiology and natural history of Parkinson's disease (PD) are not well understood. Some non-motor symptoms such as hyposmia, rapid eye movement sleep behavior disorder, and constipation may develop during the prodromal stage of PD and precede PD diagnosis by years.

OBJECTIVES: We examined the promise and pitfalls of research on premotor symptoms of PD and developed priorities and strategies to understand their clinical and etiological implications.

METHODS: This review was based on a workshop, Parkinson's Disease Premotor Symptom Symposium, held 7–8 June 2012 at the National Institute of Environmental Health Sciences in Research Triangle Park, North Carolina.

DISCUSSION: Research on premotor symptoms of PD may offer an excellent opportunity to characterize high-risk populations and to better understand PD etiology. Such research may lead to evaluation of novel etiological hypotheses such as the possibility that environmental toxicants or viruses may initiate PD pathogenesis in the gastrointestinal tract or olfactory bulb. At present, our understanding of premotor symptoms of PD is in its infancy and faces many obstacles. These symptoms are often not specific to PD and have low positive predictive value for early PD diagnosis. Further, the pathological bases and biological mechanisms of these premotor symptoms and their relevance to PD pathogenesis are poorly understood.

CONCLUSION: This is an emerging research area with important data gaps to be filled. Future research is needed to understand the prevalence of multiple premotor symptoms and their etiological relevance to PD. Animal experiments and mechanistic studies will further understanding of the biology of these premotor symptoms and test novel etiological hypothesis.

CITATION: Chen H, Burton EA, Ross GW, Huang X, Savica R, Abbott RD, Ascherio A, Caviness JN, Gao X, Gray KA, Hong JS, Kamel F, Jennings D, Kirshner A, Lawler C, Liu R, Miller GW, Nussbaum R, Peddada SD, Comstock Rick A, Ritz B, Siderowf AD, Tanner CM, Tröster AI, Zhang J. 2013. Research on the premotor symptoms of Parkinson's Disease: clinical and etiological implications. *Environ Health Perspect* 121:1245–1252; <http://dx.doi.org/10.1289/ehp.1306967>

Introduction

Parkinson's disease (PD) is the second most prevalent neurodegenerative disease and severely affects quality of life. More than 1 million older U.S. adults live with PD, and the number will double by the year 2030 (Bach et al. 2011). Clinical diagnosis of PD is currently based on the presence of motor dysfunction including rest tremor, bradykinesia, and rigidity. PD patients also suffer from a wide range of non-motor symptoms—including hyposmia (poor sense of smell), gastrointestinal dysfunction, psychiatric features (e.g., depression, anxiety, psychosis), sleep disorders, and mild-to-severe cognitive impairment—many of which are disabling and can be difficult to treat (Coelho and Ferreira 2012; Fernandez 2012) and greatly

jeopardize the quality of life of PD patients (Storch et al. 2013). Pathologically, PD has been characterized by the loss of dopamine neurons in the substantia nigra pars compacta, which underlies motor dysfunction, and by the presence of Lewy bodies in selected regions of the brain.

The cardinal motor signs of PD become clinically evident when approximately 50% of the dopaminergic neurons in the substantia nigra are lost (Fearnley and Lees 1991). Despite symptomatic therapies for dopamine deficiency–related motor features, the disease continues to progress and often leads to severe mental and physical disabilities (Coelho and Ferreira 2012; Shulman et al. 2008) and increased mortality (Chen et al. 2006; Willis et al. 2012). To date, none of the available

treatments can halt or reverse the pathological and clinical progression of PD, and novel strategies are needed. Research on disease-modifying strategies would be greatly assisted by the identification of high-risk populations.

Recent interest has focused on the non-motor symptoms of PD, some of which may

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The Parkinson's Disease Premotor Symptom Symposium was jointly supported by the intramural and extramural research programs of the National Institute of Environmental Health Sciences. We thank M. Watson and K. Gillig for their help in organizing the meeting and E.J. Zhao and E. Hood for their help in preparing this manuscript.

X.G. has a consultancy relationship with Teva; R.N. was a paid consultant for Complete Genomics Inc.; A.C.R. is an employee of the Parkinson Action Network; and A.D.S. is an employee of Avid Radiopharmaceuticals Inc. C.M.T. is an employee of the Parkinson's Institute. She serves on the Scientific Advisory Boards of the Michael J. Fox Foundation and the National Spasmodic Dystonia Association and has provided consulting services to Impax Pharmaceuticals, Adamas Pharmaceuticals, and Abbvie Pharmaceuticals. She also receives grant support from the Michael J. Fox Foundation, the Brin Foundation, James and Sharron Clark, the Parkinson's Institute and Clinical Center, the Parkinson's Disease Foundation, the U.S. Army Medical Research Acquisition Activity (the Telemedicine & Advanced Technology Research Center–managed Neurotoxin Exposure Treatment Research Program), and the National Institutes of Health, National Institute of Neurological Disorders and Stroke. A.I.T. is a consultant and/or speaker for Medtronic, St. Jude Medical, and Boston Scientific. The other authors declare they have no actual or potential competing financial interests.

The information contained in this paper does not necessarily reflect the position or the policy of the U.S. government, and no official endorsement should be inferred.

Received: 17 April 2013; Accepted: 7 August 2013; Advance Publication: 9 August 2013; Final Publication: 1 December 2013.

predate motor signs and clinical diagnosis by years ("premotor symptoms" of PD). Accumulating epidemiological and clinical evidence suggests that hyposmia (Ross et al. 2008), constipation (Abbott et al. 2007; Gao X et al. 2011; Savica et al. 2009), depression (Bower et al. 2010; Fang et al. 2010; Ishihara-Paul et al. 2008; Shiba et al. 2000), anxiety (Bower et al. 2010; Ishihara-Paul et al. 2008; Shiba et al. 2000; Weisskopf et al. 2003), rapid eye movement sleep behavior disorder (RBD) (Claassen et al. 2010; Iranzo et al. 2006; Postuma et al. 2009; Schenck et al. 1996), excessive daytime sleepiness (EDS) (Abbott

et al. 2005; Gao J et al. 2011), and autonomic dysfunction (Goldstein 2010) may occur well before the appearance of the classic motor dysfunction of PD. Evidence comes primarily from large prospective population-based cohort studies that were initially established for research on cancer and cardiovascular disease, such as the Honolulu Asia Aging Study (HAAS) (Ross et al. 2008) and the Health Professionals Follow-up Study (Gao X et al. 2011), and from retrospective examinations of archived medical records of PD cases and controls such as the Rochester Epidemiology Project (Savica et al. 2009). These findings are

summarized in Table 1. A recent meta-analysis also confirmed that constipation and mood disorders were associated with higher risk of PD (Noyce et al. 2012). Hyposmia, RBD, and EDS were not included in this meta-analysis because risk estimates either were not available or were available from only one study.

The hypothesis that premotor symptoms precede the motor signs of PD is broadly compatible with neuropathological findings reported by Braak et al. (2003). This work, although controversial (Burke et al. 2008), suggests that deposition of α -synuclein in the form of Lewy bodies and Lewy neurites

Table 1. Prospective evidence on selected premotor symptoms in large population-based studies.

Symptom	Study/reference	Age [years (mean \pm SD and/or range)]	Years of follow-up	No. of cases	Assessment	Primary results [RR/HR/OR (95% CI)]	Timeline [years prior to PD] ^a
Hyposmia	HAAS, men only (Ross et al. 2008)	79.7 \pm 4.1 (71–95)	\leq 8 years	35	BSIT score $<$ 6	Lowest vs. top two quartiles: 5.2 (1.5–25.6) for the first 4 years, 0.3 (0.0–2.7) for the second 4 years of follow-up	Within 4 years
Constipation ^b	HAAS, men only (Abbott et al. 2007)	60 (51–75)	\leq 24 years	96	Self-reported bowel movement frequency	$<$ 1/day vs. $>$ 2/day: 4.5 (1.2–16.9)	Could be \geq 12 years
	REP (Savica et al. 2009)	—	—	196	Medical record review: constipation diagnosis or laxative use	2.5 (1.5–4.1)	Could be \geq 20 years
	HPFS, men only (Gao X et al. 2011)	\sim 54–89	\leq 6 years only	156	Self-reported bowel movement frequency	\leq 2/week vs. daily: 5.0 (2.6–9.6)	6 years and probably more
	NHS, women only (Gao X et al. 2011)	\sim 36–61	\leq 24 years	402	Self-reported bowel movement frequency	Within 6 years of follow up: 2.2 (0.8–6.1); no association beyond 6 years	May limit to 6 years of follow-up
Daytime sleepiness ^c	HAAS men only (Abbott et al. 2005)	77 (71–93)	\leq 8 years	43	Self-report: single question	2.8 (1.1–6.4)	0.5–4.9 years
	NIH-AARP DH (Gao J et al. 2011)	52–71	4–10 years	770	Self-reported hours of daytime napping	\geq 1 vs. 0 hr: 1.5 (1.2–1.9)	4–10 years
RBD ^d	Mayo Clinic (Claassen et al. 2010)	21–60	Only if \geq 15 years	9 PD of 27 RBD	Clinical diagnosis	—	15–50 years
	Barcelona, Spain (Iranzo et al. 2006)	74.1(61–86)	$>$ 2 years	7 PD of 44 RBD	Clinical diagnosis	—	Could be 6–18 years
	Minnesota, men only (Schenck et al. 1996)	54.5	—	11 PD of 29 RBD	Clinical diagnosis	—	Could be by 10–29 years
	Montreal (Postuma et al. 2009)	65.4 \pm 9.3	—	19 PD of 93 RBD	Clinical diagnosis	—	On average preceded by 11 years
Depression	EPIC-Norfolk (Ishihara-Paul et al. 2008)	41–80	Median, 8 years	175	Structured questionnaire	Lifetime major depression 2.1 (1.4–2.9)	Similar results for first episode of depression before or after 40 years of age
	REP (Bower et al. 2010)	48.3 (20–69)	Mean, 29 years (up to 45 years)	156	MMPI	Quartile 4 vs. quartiles 1–3: 1.16 (0.81–1.66)	
	REP (Shiba et al. 2000)		51 years (8–87 years)	196	Medical record review	1.9 (1.1–3.2)	Within 5 years
Anxiety	EPIC-Norfolk (Ishihara-Paul et al. 2008)	41–80	Median, 8 years	175	Structured questionnaire	2.7 (1.5–4.7)	
	HPFS, men only (Weisskopf et al. 2003)	56.0 (42–77)	\leq 12 years	189	Crown–Crisp anxiety index	Score \geq 4 vs. 0–1: 1.5 (1.0–2.1)	Could be $>$ 2 years
	REP (Bower et al. 2010)	48.3 (20–69)	Mean, 29 years (up to 45 years)	156	MMPI	Quartile 4 vs. quartiles 1–3: 1.63 (1.16–2.27)/men 2.03 (1.28–3.24)/women 1.29 (0.79–2.10)	
	REP (Shiba et al. 2000)		51 years (8–87)	196	Medical record review	2.2 (1.4–3.4); slightly attenuated, even restricted to $>$ 20 years before index date	Could be $>$ 20 years

Abbreviations: BSIT, brief smell identification test; EPIC, European Prospective Investigation into Cancer; HAAS, Honolulu Asia Aging Study; HPFS, Health Professionals Follow-up Study; HR, Hazard Ratio; MMPI, Minnesota Multiphasic Personality Inventory; NHS, Nurse's Health Study; NIH-AARP DH, National Institutes of Health-AARP Diet and Health study; OR, odds ratio; RBD, rapid eye movement sleep behavior disorder; REP, Rochester Epidemiology Project; RR, relative risk.

^aThe time from measurement of non-motor symptoms to PD diagnosis are best estimates; these estimates could, however, be misleading because they were bounded by the length of follow-up and inclusion criteria. ^bThe HAAS and HPFS/NHS used the frequency of bowel movement as an indicator for constipation. ^cThe NIH-AARP DH used daytime napping duration as a surrogate for daytime sleepiness. ^dBased on follow-ups of RBD patients.

develops in the PD brain in six sequential stages. α -Synuclein pathology begins in the dorsal motor nucleus of the vagus and glossopharyngeal nerves and the anterior olfactory nucleus in stage 1, extends to the locus ceruleus and caudal raphe nuclei in the pons (stage 2), then to the substantia nigra (stage 3), to the temporal mesocortex (stage 4), and finally to the neocortex (stages 5–6). A later extension of this hypothesis further posits that the synucleinopathy may even first develop in the enteric nerves in the gut and later spread along the vagus nerve into the brain (Hawkes et al. 2007, 2009). Importantly, according to the Braak hypothesis, the irreversible loss of dopamine neurons in the substantia nigra and associated progressive motor dysfunction may not be evident until Braak stages 3 and 4. Although the Braak hypothesis is not universally supported (Burke et al. 2008; Dickson et al. 2010), it presents the intriguing possibility that the extra-nigra, nondopaminergic pathologies are intrinsic to early PD pathogenesis and that premotor symptoms could well be part of the disease's natural history (Hawkes et al. 2010).

Growing evidence on the importance of premotor symptoms, coupled with the Braak hypothesis, has generated substantial interest in understanding the origins and consequences of these symptoms. Clinical research primarily has focused on evaluating premotor symptoms and other factors as markers for the future development of PD, a subject elegantly reviewed by Berg et al. (2012). Another potential line of inquiry is based on the idea that the presence of multiple premotor symptoms in the same individual represents common underlying pathogenesis that may eventually lead to PD, and thus premotor symptoms may provide a unique opportunity to understand the etiology of PD (Hawkes et al. 2007, 2009). Despite this potential promise, little research has been carried out to understand the etiological implications of the premotor symptoms of PD.

This review was based on a workshop, Parkinson's Disease Premotor Symptom Symposium, held 7–8 June 2012 at the National Institute of Environmental Health Sciences in Research Triangle Park, North Carolina.

A comprehensive review of the clinical and epidemiological evidence for the existence of these premotor symptoms in PD is outside the scope of this review. Instead, we focus on outlining the promises and pitfalls of the concept of premotor symptoms and on developing research priorities and strategies for understanding the clinical and etiological implications of these symptoms. Although these symptoms can also develop after the clinical diagnosis of PD, for this review, we focus on the period prior to the emergence of diagnostic motor abnormalities.

Identification of High-Risk Populations

Several important studies have tested the hypothesis that premotor symptoms, coupled with neuroimaging, may lead to early identification, or even diagnosis, of PD (Lang 2011; Tolosa et al. 2009). Preliminary results have been published from the Prospective Evaluation of Risk Factors for Idiopathic Parkinson's Syndrome (PRIPS) study (Berg et al. 2013) and the Parkinson At-Risk Syndrome (PARS) study (Siderowf et al. 2012). PRIPS aimed to test a two-stage screening strategy for early identification of PD cases utilizing the following predictors: hyposmia, PD family history, subtle motor impairment, and substantia nigra hyper-echogenicity (SN+). This general population-based cohort recruited 1,352 participants ≥ 50 years of age (mean age, 59 years). Hyposmia was evaluated using the Sniffin' Stick test (Hummel et al. 2001) and SN+ by transcranial sonography. A total of 10 participants developed PD during approximately 3 years of follow-up. Hyposmia was strongly associated with the risk of developing PD with sensitivity and specificity both $> 70\%$. The positive predictive value (PPV), however, was only 2%, in part due to the low PD incidence in this relatively young population. Combining hyposmia with other characteristics (e.g., family history or SN+) only slightly increased the PPV, but substantially decreased the sensitivity. Unlike the PRIPS study, PARS was conducted among a risk-enriched population in which 45% of the 4,999 study participants (mean age, 64 years) had a family history of PD. The study was designed to evaluate a two-stage strategy of at-risk identification: olfactory testing using the University of Pennsylvania Smell Identification Test (Doty et al. 1984), followed by dopamine-transporter (DAT) imaging. Although findings on the DAT scan portion are yet to be published, preliminary analyses showed that participants with hyposmia were more likely to have other non-motor features and to report changes in motor function (Siderowf et al. 2012).

Of the premotor symptoms, the PRIPS and PARS studies focused on hyposmia. The results from these studies, albeit preliminary, clearly show that an individual premotor symptom by itself is inadequate for early disease identification. This is actually what one would expect for a relatively rare disease such as PD because the PPV depends on the prevalence of pre-diagnostic cases in the target population.

The utility of combinations of premotor symptoms for early disease identification has been little explored and merits consideration. Although the underlying etiologies of premotor symptoms in the general population are likely diverse, the presence of multiple symptoms in individuals who later develop

PD may reflect common or similar underlying pathologies, for example Lewy pathology in various sites of the brain, spinal cord, and autonomic nervous system. In support of this notion, in the HAAS, both the sense of smell (Ross et al. 2006) and bowel movement frequency (Abbott et al. 2007) were strongly related to incidental Lewy body disease among individuals without PD. Further, α -synuclein was identified from colon tissues of PD patients collected 2–5 years before PD motor onset (Shannon et al. 2012), but not in any of the controls.

One may further hypothesize that among individuals who will develop PD, multiple premotor symptoms develop over time as a result of common pathologies and eventually become a clinically recognizable syndrome several years before PD diagnosis (Figure 1). In contrast, among individuals who will not develop PD, these symptoms may also exist, but they are more independent of each other and more randomly distributed over the entire life period. Therefore, the joint prevalence of multiple premotor symptoms in a low-risk population will be low. These hypotheses are yet to be systematically examined, but there are preliminary supportive data. Based on hyposmia, infrequent bowel movement, slow reaction time, and excessive daytime sleepiness, the HAAS showed that 2 of the 24 individuals with more than three of these symptoms developed PD within 4.6 years of follow-up, as compared with 8 of 852 for those with only one symptom (Berg et al. 2012). Preliminary evidence also comes from research in high-risk populations. Non-Parkinsonian family members of patients with the leucine-rich repeat kinase 2 (*LRRK2* G2019S) mutation showed more constipation and poorer color discrimination than controls (Marras et al. 2011). Therefore, preliminary evidence does suggest that multiple non-motor symptoms tend to cooccur among individuals at higher risk for PD.

It is also important to understand when multiple premotor symptoms become detectable in the prodromal stage of PD. Ideally, this should be investigated in large prospective cohorts with long follow-up and repeated measurements of multiple premotor symptoms. In reality, we have just begun to understand the temporal relationships between individual symptoms and PD by examining existing clinical data or data from prospective cohorts (Table 1). For example, several clinical studies have consistently documented RBD onset about 10–20 years before PD onset (Boeve and Saper 2006; Claassen et al. 2010; Iranzo et al. 2006; Postuma et al. 2009; Schenck et al. 1996). These were studies of RBD patients who were diagnosed by polysomnography, and it has yet to be determined whether this clinical observation can

be generalized to the general elderly population where only questionnaire-based screening for probable RBD is possible (Postuma et al. 2012a). Data on the timing of other key premotor symptoms are limited or inconsistent. For example, several studies showed that constipation might precede PD clinical diagnosis by 10–20 years in men (Abbott et al. 2001; Gao X et al. 2011; Savica et al. 2009), but data are not consistent in women (Gao X et al. 2011; Savica et al. 2009). The population-based HAAS showed that hyposmia was highly predictive of PD onset within 4 years after symptom assessment (Ross et al. 2008). Two other studies among high-risk individuals (Ponsen et al. 2009; Postuma et al. 2011) showed that hyposmia predicted PD risk throughout the entire follow-up period of 5 years. Because the assessment of temporal relationship will be bounded by the length of follow-up, future studies should have longer periods of follow-up and repeated symptom assessments. More importantly, future studies should also investigate the temporal pattern of multiple premotor symptoms in prodromal PD cases.

Measuring premotor symptoms for neurodegeneration research represents a substantial challenge. Studies to date have mostly used simple methods to identify premotor symptoms, including methods such as self-reported symptoms, self-reported diagnoses, screening tests, and structured questionnaires. For example, the sense of smell is often measured with simple screening tests such as the Brief Smell Identification Test (Ross et al.

2008) or the Sniffin' Stick Test (Hummel et al. 2001), and hyposmia is defined as a score below population norms. These simple methods have served well to establish the associations between premotor symptoms and PD. However, because most premotor symptoms are common in the elderly and are etiologically heterogeneous (Doty 2009; Leung et al. 2011), novel approaches are needed to assess various modalities of these symptoms and to identify patterns that are more specific to PD. Compared to other premotor symptoms, RBD is more specific; however, its diagnosis requires polysomnographic confirmation at sleep clinics. Several screening questionnaires for probable RBD (Boeve et al. 2011; Li et al. 2009; Postuma et al. 2012a; Stiasny-Kolster et al. 2007) have been developed and validated in clinical settings, but their validities in identifying RBD patients from the general population are yet to be evaluated.

A large prospective study reported subjective complaints of motor dysfunctions such as stiffness and tremor prior to PD diagnosis (de Lau et al. 2006). In fact, subtle motor abnormalities have been quantitatively documented among individuals at high risk for PD. For example, Mirelman et al. (2011) reported subtle gait changes among asymptomatic carriers of *LRRK2* mutation with quantified gait analyses under challenged conditions. Among RBD patients, Postuma et al. (2012b) documented multiple motor abnormalities on average 6–8 years prior to PD diagnosis, including voice and face

akinesia, rigidity, abnormal gait, limb bradykinesia. Evaluation of subtle motor changes in addition to premotor symptoms may prove important in differentiating PD from other causes of non-motor symptoms. Further, the development and use of standardized assessment tools for non-motor and motor symptoms such as the National Institutes of Health/National Institute of Neurological Disorders and Stroke (NIH/NINDS) common data elements for PD will greatly facilitate such research (NINDS 2013).

Implications for Parkinson's Etiology and Experimental Research

An inherent implication of research on premotor symptoms is that it may eventually lead to a better understanding of PD etiology (Hawkes et al. 2007, 2009). The concept that premotor symptoms represent intermediate phenotypes prior to overt PD may offer us a vehicle to understand the roles of genetics and environment in the early stages of PD development. For example, neurotoxins or viruses may enter the body via the nasal cavity or the digestive tract (Hawkes et al. 2007, 2009), and, in susceptible individuals, may initiate Lewy pathology in the olfactory bulb or the enteric nerves (Doty 2008; Hawkes et al. 2007, 2009; Reichmann 2011); over time, this may lead to premotor symptoms such as hyposmia or constipation and may eventually progress to PD. It is therefore important to identify environmental and genetic factors associated with the presence of multiple premotor symptoms and, more importantly, to identify factors that may prevent the progression of premotor symptoms to clinical PD. This concept is illustrated in Figure 2.

To the best of our knowledge, no epidemiological study has examined common etiological factors for the presence of multiple non-motor symptoms. Preliminary data are available only on risk factors for individual symptoms. Postuma et al. (2012c) recently published the first report on environmental risk factors for RBD. In this multicenter study of 347 cases and 347 controls, RBD was positively associated with pesticide exposure and head injury. However, unlike PD, RBD was more common among smokers and was not related to caffeine intake. More studies have examined risk factors associated with hyposmia. All studies found that the risk of hyposmia increases with age and is higher in men than in women (Brämerson et al. 2004; Schubert et al. 2011, 2012; Siderowf et al. 2007, 2012; Vennemann et al. 2008). Data on smoking or coffee drinking and hyposmia are, however, preliminary and inconsistent (Brämerson et al. 2004; Schubert et al. 2011, 2012; Siderowf et al. 2007, 2012; Vennemann

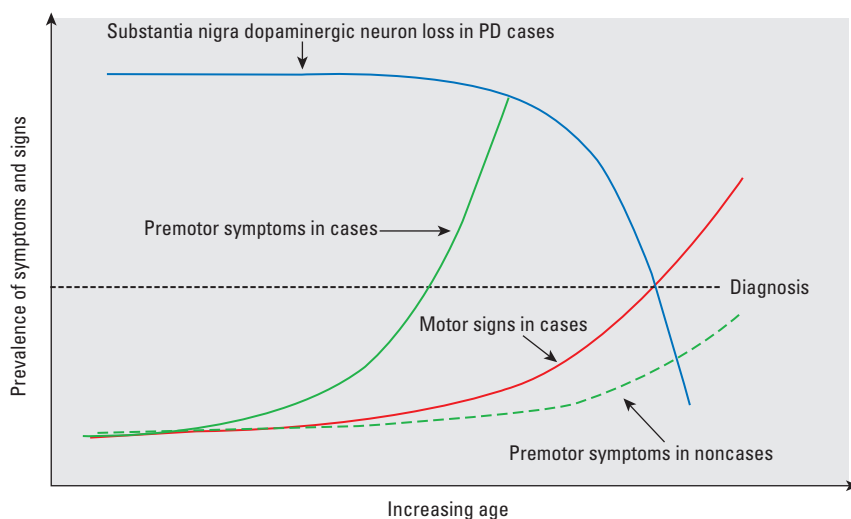


Figure 1. A hypothesis on the development of premotor symptoms among persons who will or will not develop PD in lifetime. The green lines represent the joint prevalence of multiple premotor symptoms by age; solid, future PD cases, and dashed for noncases. The red line represents motor signs among future PD patients. The blue line represents the loss of dopaminergic neurons in the substantia nigra pars compacta of PD patients which underlies cardinal motor signs. PD diagnosis is made based on cardinal motor signs (red) when approximately 50% of the dopaminergic neurons in the substantia nigra have been lost (threshold shown as the black dotted line). Individuals at high risk for PD (solid green line) will develop multiple premotor symptoms years before onset of PD motor signs; for individuals who will not develop PD (dashed green line), the joint prevalence of these symptoms remain at low level even at older age.

et al. 2008), although current smoking is associated with a higher risk of hyposmia in some studies (Schubert et al. 2012; Vennemann et al. 2008). In adults, the prevalence of constipation is higher in women and increases modestly with age (McCrea et al. 2009; Soares and Ford 2011). Other suspected risk factors for constipation include inadequate fluid or dietary fiber intake, less physical activity, concurrent use of certain medications, levels of thyroid hormone and progesterone, and a wide range of medical conditions including neurodegenerative diseases (Leung 2007; Leung et al. 2011). Therefore, risk factors for individual non-motor symptoms are diverse, and PD-related pathology is probably only a small contributor to the prevalence of each of these symptoms. Combining multiple pre-motor symptoms may rule out some diverse pathologies unrelated to PD. Further, PD is likely to be phenotypically and etiologically heterogeneous (van Rooden et al. 2009, 2011); and careful phenotyping of various PD motor and non-motor symptoms may help us understand the interrelationship among risk factors, premotor symptoms, and neurodegeneration.

Although human observational studies are essential to define premotor symptoms and their relationship to PD development, experimental studies are needed to understand the underlying biology and to examine novel etiological hypotheses. For example, could the gastrointestinal tract or the olfactory bulb be the sites of initial exposure to a pathogenic environmental agent (Reichmann 2011)? Does pathology progress anatomically, as the Braak hypothesis predicts (Pan-Montojo et al. 2012)? Does the selectivity and order of neurodegeneration in PD reflect differential sensitivity to environmental agents or some other mechanism of progression such as prion-like spreading (Dunning et al. 2012)? Experimental research that models prodromal PD may help answer these questions.

Animal models based on toxicants [e.g., 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP), 6-hydroxydopamine (6-OHDA), paraquat, rotenone] and those based on genes [e.g., *SNCA* (α -synuclein), *LRRK2*, *PINK1* (PTEN-induced putative kinase 1), *PARK2* (parkin)] have been used for PD research (Bezard et al. 2012; Blesa et al. 2012). These models were developed to mimic features of late-stage PD such as dopaminergic neuron loss and motor dysfunction, or to recapitulate particular pathogenic processes such as neuroinflammation. The extent to which current models replicate the non-motor features of PD is incompletely known at present, although recent work has revealed some intriguing results suggesting abnormalities analogous to non-motor features of PD (Jellinger 2011; McDowell and Chesselet 2012; Smith et al. 2012).

Central to this work is the availability of validated methods to evaluate olfaction, gastrointestinal function, sleep disturbances, or depression/anxiety in experimental animals. The technical difficulties of reliably determining the presence or absence of these non-motor features in experimental animals are not trivial. Furthermore, the mechanistic relationship between abnormalities observed in the commonly used assays in experimental animals and the analogous symptoms in human patients is uncertain, especially for complex behavioral traits such as depression and anxiety. Nonetheless, ways to evaluate these non-motor symptoms have been reported in mice, rats, primates, and zebrafish. Each of these animals shows phylogenetic conservation of neuroanatomical structures involved in early Braak stages of PD pathology, suggesting that they might be employed as models to study premotor PD.

So far, a number of animal models of PD have shown either non-motor functional abnormalities or pathology outside the substantia nigra. Olfactory function has been shown to be abnormal in MPTP-treated rodents (Schintu et al. 2009), transgenic mice expressing α -synuclein under a neuronal regulatory element derived from the *Thy1* gene (*Thy1- α Syn*) (Fleming et al. 2008), and mice expressing reduced levels of the vesicular monoamine transporter (VMAT) (Taylor et al. 2009). Sleep and circadian rhythm are known to be disrupted in MPTP-treated rodents (Laloux et al. 2008), rotenone-treated rats (García-García et al. 2005), and *Thy1- α Syn* mice and VMAT2-deficient mice (Taylor et al. 2009). Gastrointestinal function has been shown to be abnormal in MPTP-treated mice (Anderson et al. 2007), rotenone-treated rats (Drolet et al. 2009), *Thy1- α Syn* mice (Wang et al. 2008, 2012), *SNCA* PAC mice (which express mutant human α -synuclein from a P1 artificial chromosome containing its endogenous regulatory elements) (Kuo et al. 2010),

and VMAT2-deficient mice (Taylor et al. 2009). These findings are of interest because they demonstrate that toxicant exposures and genetic manipulations used to induce motor signs of PD can also induce non-motor features. This suggests that at least some of the neuronal populations underlying non-motor symptoms share susceptibility with dopamine neurons to agents implicated in motor PD pathogenesis. This is consistent with a model in which common etiological mechanisms could underlie both motor and non-motor components of the disease.

Interestingly, a few of the models have shown ordered progression from non-motor to motor symptoms. *Thy1- α Syn* transgenic mice showed α -synuclein inclusions in the olfactory bulb and deficits in olfactory function on multiple tests by 3 months of age (Fleming et al. 2008). By this time point, animals also showed progressively worsening sleep abnormalities (Kudo et al. 2011) and progressive reduction in stool frequency (Wang et al. 2012). These changes preceded loss of striatal dopamine, which did not occur until 14 months of age (Lam et al. 2011). Similarly, VMAT2-deficient mice demonstrated progressive non-motor symptoms prior to the onset of motor deficits (Taylor et al. 2009). Gastrointestinal dysfunction was seen at 2 months of age, olfactory defects by 5 months, and anxiety-like behavior at 6 months. L-dihydroxyphenylalanine (L-DOPA)-responsive hypokinesia and loss of striatal tyrosine hydroxylase terminals were present by 18 months of age, and loss of nigral dopamine neurons worsened between 18 and 24 months (Caudle et al. 2007). Data from both models imply that a systemic abnormality affecting all cells can result in specific abnormalities of neuronal populations implicated in non-motor and motor PD with replication of some of the temporal course.

These data do not yet allow us to distinguish between a model for pathogenic

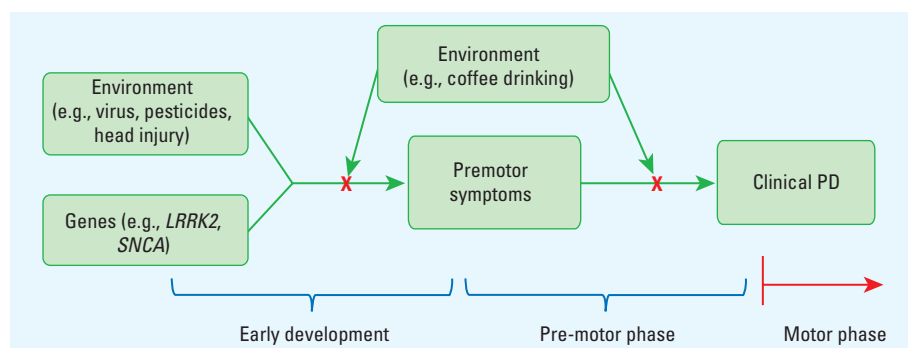


Figure 2. A hypothesis on risk factors, premotor symptoms, and PD. Environmental or genetic factors may initiate neurodegeneration through mechanisms such as neuroinflammation; in susceptible individuals, this may first lead to premotor symptoms years before PD clinical onset; if this neurodegeneration continues without effective intervention, premotor symptoms may eventually progress into overt PD; however, with interventions such as coffee drinking, this premotor progression may be halted before it becomes irreversible.

progression in which the temporal course of the disease is dictated by the differential vulnerability of various neuronal groups to a systemic abnormality and an alternative model in which pathology spreads anatomically from one site of the nervous system to another to produce progressive symptoms. Much recent attention has been given to the idea that α -synuclein has prion-like properties and that α -synucleinopathy can spread from a site of initial pathology to other regions of the central nervous system (CNS) by axonal transport and cell-to-cell spread (Luk et al. 2012). In this regard, it is noteworthy that the pathology in both Thy1- α Syn mice (Fleming et al. 2004) and VMAT2-deficient mice (Taylor et al. 2009) is dependent on the presence of α -synuclein. However, several alternative explanations for the progression of disease are equally consistent with the available data and further studies will be necessary to determine whether progression can be arrested by interventions that prevent the transport or transmission of pathological α -synuclein species, or whether additional cellular factors dictate the differential vulnerability of neuronal groups involved in non-motor symptoms.

The hypothesis that an environmental agent could provoke pathology at an anatomical site of entry that then progresses to involve other structures, culminating in degeneration of the substantia nigra, has received some preliminary experimental support. For example, Jang et al. (2009) reported that, in mice, intranasally injected H5N1 influenza virus travelled from the enteric nervous system (ENS) into the CNS and eventually caused degeneration of dopaminergic neurons. Further, this sequence was accompanied by chronic neuroinflammation with microglial activation and elevated expression of cytokines (Jang et al. 2012). These findings imply that initiating pathogenic events can provoke distinct secondary mechanisms underlying disease progression, with the important implication that environmental agents that trigger early events in PD pathogenesis may no longer be present at the end stage of the disease, when tissue samples are generally available for analysis.

The gastrointestinal tract is potentially an important site for exposure to environmental agents, and the suggestion that α -synuclein pathology in the ENS may be one of the first abnormalities in PD patients has promoted interest in the possibility of modeling pathology in the ENS and its subsequent progression to the CNS. Transgenic mice expressing human α -synuclein under its own regulatory elements showed prominent ENS pathology, but no progression to other features of PD (Kuo et al. 2010), suggesting that a second event was necessary to promote disease progression. Recent reports showed

that intragastric rotenone caused α -synuclein aggregation in mice, following a staged pattern that was consistent with the Braak hypothesis (Pan-Montojo and Funk 2010; Pan-Montojo et al. 2010), and resection of the autonomic nerves prevented this progression (Pan-Montojo et al. 2012). These interesting observations are yet to be replicated by other laboratories, and their interpretation consequently remains speculative. However, the local microenvironment of the gastrointestinal tract remains a potentially significant factor in dictating initiating pathogenic events, and is worthy of further investigation. This might also encompass evaluation of the role of the gut microbiome, which could be experimentally manipulated in animal models to determine whether alterations can initiate PD pathology or modulate the time course of onset of pathology and progression. Although few empirical data exist regarding the role of the microbiome in PD, the microbiome influences the immune system, gastrointestinal mobility, and the metabolism of nutrients and other exogenous chemicals (Grenham et al. 2011), all of which may potentially contribute to the development of PD. Similarly, experimental animals could be exposed to toxicants through the gastrointestinal tract to evaluate whether etiologically implicated exogenous agents can provoke the earliest pathological changes of PD or modulate their appearance in experimental models. These studies could provide valuable mechanistic insights and generate further hypotheses to be addressed in human studies.

Finally, although this review focuses on PD, research on premotor symptoms may have broader implications because many of these symptoms have been linked to other neurological diseases. For example, hypoxemia is associated with higher risk of cognitive decline and Alzheimer's disease (Wilson et al. 2007, 2009), and RBD precedes Lewy body dementia and multiple system atrophy (Schenck et al. 2013). Further, olfactory dysfunction has been documented in schizophrenic patients and individuals at high risk for schizophrenia (Moberg et al. 2013). Therefore research on premotor symptoms may eventually provide novel insights into the natural history and etiology of neurodegeneration and related conditions in addition to PD, and into the complex interrelationships among these conditions.

Conclusion

Premotor symptoms of PD may offer us an excellent opportunity to identify populations at higher risk for PD and to understand early disease etiology. Further research is needed to understand whether the presence of multiple premotor symptoms is predictive of PD. Animal experiments may help to understand

the biology of these non-motor symptoms and test novel etiological hypothesis. At the current time, our understanding of these premotor symptoms is still in its infancy and the research calls for close multidisciplinary collaborations among clinicians, epidemiologists, basic scientists, and geneticists.

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